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## Three Dimensional Cloud Dynamics: Preliminary Application to a HANE Environment

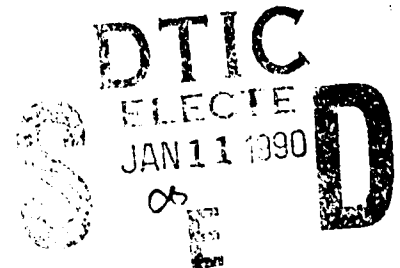
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# THREE DIMENSIONAL CLOUD DYNAMICS: PRELIMINARY APPLICATION TO A HANE ENVIRONMENT

## I. INTRODUCTION

The Defense Nuclear Agency is sponsoring a broad-based research program on the dynamics and phenomenology of high altitude nuclear explosions (HANEs). An important goal of this research is to understand and model the late time nuclear environment; specifically, the intense field-aligned striations which are produced. These striations are regions of high electron density and are of military significance because they can adversely impact communication and surveillance systems. Of particular interest to DNA is the development of a model which characterizes the power spectral density of nuclear striations: the outer scale, the freezing scale, the inner scale, and the associated power law exponents between these scale sizes. This information provides a description of the late time nuclear environment which can be used in propagation codes relevant to military systems. —————> See #1473

It is generally believed that the outer scale is related to the macroscopic size of the striations (or clumps of striations), while the inner scale is related to dissipative effects (i.e., diffusion). The freezing scale length is associated with plasma dynamics at scale sizes between the inner and outer scale length and is associated with a 'break' in the power law exponent. This type of power spectral density is observed in naturally occurring structured ionospheric environments (e.g., equatorial spread F, high latitude blobs). Since it is believed that the fundamental structuring processes are the same in both the ambient and HANE environments, then it is expected that the power spectral densities will be similar, at least qualitatively.

Recently, DNA researchers have focussed on developing a model for the freezing scale length ( $k_f^{-1}$ ) which can be implemented in conjunction with the DNA code SCENARIO. One freezing model that has been developed is the

JAYCOR freezing model (Sperling et al., 1988). This model attributes the freezing scale length to collisional viscosity and/or magnetic viscosity depending on the ionospheric parameters. This model emphasizes the dynamics of the plasma transverse to the magnetic field and incorporates parallel effects in a qualitative manner. In contrast to this model, recent studies at NRL (Drake and Huba, 1986; 1987; Drake et al., 1988) have shown that parallel dynamics (i.e., 3D effects) can play the key role in the 'freezing' of plasma clouds (or striations). In particular, a stability criterion has been derived which indicates that plasma clouds (or striations) are stable against large-scale structuring when  $r_c > r_{cr}$ ; here  $r_c$  is the radius of the cloud transverse to  $\vec{B}$ , and  $r_{cr}$  is a 'critical' radius which is a function of the physical parameters of the system. The purpose of this report is to present quantitative estimates of  $r_{cr}$  for parameters typical of barium clouds and nuclear striations based upon the NRL 3D model and to discuss the implications of these results regarding the freezing scale length.

For the case of barium clouds, we find the critical scale size for marginal stability is  $r_{cr} \lesssim 100$  m, i.e., barium clouds with  $r_c > r_{cr}$  are stable. Since the scale size of 'frozen' barium clouds is  $\sim 100$ 's m, we conclude that our theoretical results are consistent with the observations: 3D effects can provide the physical mechanism to 'freeze' barium clouds at the observed scale sizes. Although this result is very significant, it does not explain the actual scale size of the striations. We suggest the following hypothesis regarding the structuring of barium clouds. During the initial phase of a barium cloud expansion, the cloud evolves dynamically. The cloud diffuses along the magnetic field, and in the presence of a neutral wind or ambient electric field it steepens on one side. Eventually, the steepened 'backside' of the cloud can become

unstable to the  $\underline{E} \times \underline{B}$  instability and the cloud structures. During this phase, the waterbag cloud model used in our 3D theory is not appropriate, and hence, our theory is not applicable. This is not to say that 3D effects are not important during the onset of instability, but only that the quantitative analysis in Drake et al. (1988) is not valid. Subsequent to the initial break-up of the cloud, the smaller clouds (or fingers) may evolve into waterbag-like equilibria. If this is the case, then we can apply the NRL 3D model and ask the question: Are these smaller clouds stable or unstable? If they are stable, as our analysis indicates, then 3D effects can account for 'freezing'. As to the distribution of frozen scale sizes, this would be determined by the initial break-up of the cloud.

Applying our model to plasma parameters believed typical of nuclear striations, we find that the critical scale size is in the range  $r_{cr} \approx 10$ 's m - 100's km. The reason for this rather broad range of values is due to the broad parameter regime considered. Thus, unlike the situation for barium clouds, it is not clear that the initial set of nuclear striations will be stable to further structuring because of 3D effects. Nevertheless, early time structuring ( $t \lesssim$  few min) will probably play an important role in setting up a distribution of striation scale sizes which may affect late time phenomenology, and hence should be more thoroughly investigated.

## II. CRITICAL RADIUS MODEL

The plasma and field configuration used in Drake et al. (1988) is described as follows. The magnetic field is in the z-direction ( $\underline{B} = B \hat{e}_z$ ), the neutral wind is in the x-direction ( $\underline{V}_n = V_n \hat{e}_x$ ), and a waterbag model is assumed for the density, i.e.,  $n_0 = n_c + n_b$  inside the cloud and  $n_0 = n_b$  outside the cloud where the subscripts c and b denote cloud and background,

respectively. The cloud is assumed to be circular in the plane transverse to  $\underline{B}$  and is an arbitrary ellipse in the plane containing  $\underline{B}$ .

The equilibrium potential for this configuration consists of two components: a polarization potential caused by the neutral wind, and an ambipolar potential caused by electron pressure parallel to  $\underline{B}$ . The polarization potential causes the cloud to move in the direction of the neutral wind (albeit at a reduced speed). The relative ion-neutral slip velocity is the driving mechanism for the gradient drift instability which can cause the cloud to structure. The ambipolar potential causes the cloud to spin about the axis aligned with the magnetic field. The rotation rate varies with position along the length of the cloud (i.e., along  $\underline{B}$ ), so that there is a 'shear' in the cloud velocity in this direction.

A stability analysis was performed based upon this equilibrium and a stability criterion was derived [Drake et al., 1988]. The marginal stability criterion for the cloud is given by

$$\Gamma = \Gamma_c \quad (1)$$

where

$$\Gamma = \frac{c(T_e + T_i)}{eB} \frac{1}{V_n} \frac{1}{r_c} \quad (2)$$

$$\Gamma_c = z_c^2 \left(1 - \frac{V_0}{V_n}\right) \cos \phi_0 \quad (3)$$

where  $\phi_0$  is determined from

$$\omega_0(\phi_0, \Gamma_c, M, z_c) = 0 \quad (4)$$



These expressions are (52a) and (52b) in Drake et al. (1988). Here,  $r_c$  is the radius of the cloud,  $z_c = (L_z/r_c)(\sigma_\perp/\sigma_\parallel)^{1/2}$ ,  $L_z$  is the half-length of the cloud along  $\underline{B}$ ,  $\sigma_{\parallel,\perp}$  are the parallel and perpendicular conductivities, respectively,  $[\sigma_\parallel/\sigma_\perp = (\Omega_e \Omega_i / \nu_e \nu_i)^{1/2}$  where  $\Omega_\alpha$  is the cyclotron frequency of species  $\alpha$ ,  $\nu_e = \nu_{ei} + \nu_{en}$  and  $\nu_{\alpha\beta}$  is the collision frequency between species  $\alpha$  and  $\beta$ ],  $M = n_c/n_b$ ,  $\phi_0$  is the azimuthal angle for mode localization,  $V_0$  is the cloud speed, and  $\omega_0$  is the azimuthal mode frequency. Clouds are stable for  $\Gamma > \Gamma_c$  and are unstable for  $\Gamma < \Gamma_c$ .

This stability criterion is based upon two distinct physical effects: convection and shear. First, the condition  $\omega_0 = 0$  requires the mode to be non-propagating; this results from a balance of the diamagnetic propagation of the mode, and the azimuthal background plasma flow. If this condition cannot be met, then the cloud is stable because perturbations are rapidly convected from the unstable 'backside' of the cloud to the stable 'front-side' of the cloud. This stabilizing mechanism is discussed in detail in Drake and Huba (1986). The second stabilizing mechanism results from shear stabilization. As noted earlier, the azimuthal flows generated by the ambipolar potential are not uniform along the length of the cloud. This sheared flow causes the perturbations to have  $k_z \neq 0$  which gives rise to the damping of the mode. This point is discussed in detail in Drake et al. (1988).

The stability criterion can be simplified by considering the limits  $z_c \gg 1$ ,  $z_c = 1$ , and  $z_c \ll 1$  (Drake et al., 1988). We find that (3) can be written as

$$\begin{aligned}
 2z_c^2 \cos\phi_0 / (M+2) & \quad z_c \gg 1 \\
 \Gamma_c = 2z_c^2 \cos\phi_0 / (M+3) & \quad z_c = 1 \\
 (2/\pi)z_c^2 \cos\phi_0 / (2/\pi + Mz_c) & \quad z_c \ll 1
 \end{aligned} \tag{5}$$

We further simplify (5) by taking  $\phi_0 \sim 0^\circ$  for  $z_c < 1$  and  $\phi_0 \sim 45^\circ$  for  $z_c \geq 1$ . This approximation is based upon exact solutions to (1) - (4), and is used in order to develop a simple model for the critical cloud radius. We obtain the following marginal stability condition

$$\begin{aligned} \sqrt{2} z_c^2 / (M+2) & & z_c \gg 1 \\ \Gamma = \Gamma_c \equiv 3\sqrt{2} z_c^2 / 2(M+3) & & z_c = 1 \\ (2/\pi) z_c^2 / (2/\pi + M z_c) & & z_c \ll 1 \end{aligned} \quad (6)$$

However, we note that our goal is to determine a critical striation radius,  $r_{cr}$ , based upon (6). In order to do this we proceed in the following manner. We define  $\Gamma_0$  as follows

$$\Gamma_0 = \frac{c(T_e + T_i)}{eB} \frac{1}{V_n} \frac{1}{L_z} \left( \frac{\sigma_{||}}{\sigma_{\perp}} \right)^{1/2} \quad (7)$$

so that

$$\Gamma = \Gamma_0 z_c. \quad (8)$$

Substituting (8) into the marginal stability condition (6) we arrive at a new marginal stability condition

$$\begin{aligned} \sqrt{2} z_c / (M+2) & & z_c \gg 1 \\ \Gamma_0 = \Gamma_{c0} \equiv 3\sqrt{2} z_c / 2(M+3) & & z_c = 1 \\ (2/\pi) z_c / (2/\pi + M z_c) & & z_c \ll 1 \end{aligned} \quad (9)$$

The advantage of using (9) instead of (6) is that  $\Gamma_0$  does not depend on the transverse radius of the cloud (or striation).

Based upon (9) we determine the critical radius,  $r_{cr}$ , as follows. First, we plot  $\Gamma_{c0}$  vs.  $z_c$  for a specific value of  $M$ . This is shown in Fig. 1 for  $M = 5.0$ ; note that  $\Gamma_{c0}$  increases monotonically with increasing  $z_c$ . In calculating  $\Gamma_{c0}$  we use (9) for  $z_c > 10$ ,  $z_c = 1$ , and  $z_c < 0.1$ . The values of  $\Gamma_{c0}$  between  $z_c = 0.1$  and  $1.0$ , and  $z_c = 1.0$  and  $10.0$  are calculated assuming linear interpolation between these points. We find this to be a reasonable approximation based upon comparisons with exact solutions of  $\Gamma_{c0}$  using the formulas in Drake et al. (1988). Second, we calculate the value of  $\Gamma_0$  and plot it as a straight line. For illustrative purposes we assume  $\Gamma_0 = 0.5$  in Fig. 1. The marginal stability condition is determined by  $\Gamma_0 = \Gamma_{c0}$ . Clouds are stable for  $\Gamma_0 > \Gamma_{c0}$  and unstable for  $\Gamma_0 < \Gamma_{c0}$ . This means that clouds are stable for  $z_c < z_{cr}$  and unstable for  $z_c > z_{cr}$  where  $z_{cr} \approx 2.2$  in Fig. 1. Noting that  $z_c = (L_z/r_c)(\sigma_{\perp}/\sigma_{\parallel})^{1/2}$  we then define the critical radius to be

$$r_{cr} = \frac{L_z}{z_{cr}} \left( \frac{\sigma_{\perp}}{\sigma_{\parallel}} \right)^{1/2} \quad (10)$$

Thus, clouds are stable for  $r_c > r_{cr}$  and are unstable for  $r_c < r_{cr}$ . The explicit dependence of  $r_{cr}$  on the various parameters (e.g.,  $L_z$ ,  $V_n$ ,  $\sigma_{\parallel}/\sigma_{\perp}$ , etc.) is described in the Appendix.

### III. QUANTITATIVE RESULTS

We now present a series of figures which plot  $r_{cr}$  as a function of different physical parameters representative of barium clouds and nuclear striations.

First, we consider barium clouds. In Fig. 2 we plot  $r_{cr}$  (meters) vs.  $\sigma_{\parallel}/\sigma_{\perp}$  for  $M = 10$ ,  $T_e = T_i = 0.1$  eV,  $B = 0.3$  G,  $V_n = 100$  m/sec, and  $L_z = 5$  km, 10 km, 15 km, 20 km, and 40 km. Barium clouds are observed to structure when  $L_z \sim 15 - 30$  km [Linson, 1972]. For clouds at altitudes ~

180 km we estimate  $\sigma_{||}/\sigma_{\perp} \sim 6.25 \times 10^4$ . From Fig. 2 we see that  $r_{cr} \lesssim 10$ 's m for  $L_z < 40$  km. Thus, barium clouds with transverse scale sizes greater than 10's m are stable to further structuring by the gradient drift instability because of 3D effects. This is consistent with observational evidence which suggests that barium clouds are frozen for  $r_c \sim 100$ 's m. However, we add that the critical radius determined by our theory does not predict the predominance of cloud striations with  $r_c \sim 100$ 's m. We discuss this point further in the final section.

We now turn our attention to parameters typical of nuclear striations. In Fig. 3 we plot  $r_{cr}$  (km) vs.  $\sigma_{||}/\sigma_{\perp}$  for  $L_z = 200$  km,  $V_n = 10^3$  m/sec,  $T_e = T_i = 0.3$  eV,  $B = 0.3$  G, and  $M = 5.0, 10.0, 20.0$ , and  $100.0$ . First, we note that in general,  $r_{cr}$  decreases as  $M$  increases. Second, as in the case of barium clouds, there is a relatively strong dependence of  $r_{cr}$  on  $\sigma_{||}/\sigma_{\perp}$ . For  $\sigma_{||}/\sigma_{\perp} \gtrsim 4.0 \times 10^6$  we note that  $r_{cr} < 100$ 's m for the values of  $M$  chosen. However, for more collisional striations (i.e.,  $\sigma_{||}/\sigma_{\perp} \lesssim 2.0 \times 10^5$ ), the critical radius for low to moderate  $M$  values is  $\gtrsim 10$  km, while for high  $M$  values is  $\sim 100$ 's m. And third, note that  $r_{cr}$  becomes independent of  $M$  for  $\sigma_{||}/\sigma_{\perp} < 10^4$  and  $M \lesssim 20$ ; for these parameters we also have  $z_{cr} \ll 1$ . This result is consistent with (10).

In Fig. 4 we plot  $r_{cr}$  (km) vs.  $\sigma_{||}/\sigma_{\perp}$  for  $M = 10$ ,  $V_n = 10^3$  m/sec,  $T_e = T_i = 0.3$  eV,  $B = 0.3$  G, and  $L_z = 100$  km,  $200$  km,  $300$  km, and  $400$  km. The values of  $r_{cr}$  are similar to those in Fig. 3, ranging from 10's m to 100's km. We note that  $r_{cr}$  decreases as  $L_z$  decreases as expected. For relatively short striations ( $L_z \sim 100$  km), we find that  $r_{cr} \lesssim 10$  km while for longer striations ( $L_z \sim 400$  km) that  $r_{cr} \lesssim 100$ 's km.

In Fig. 5 we plot  $r_{cr}$  (km) vs.  $\sigma_{||}/\sigma_{\perp}$  for  $M = 10$ ,  $T_e = T_i = 0.3$  eV,  $B = 0.3$  G,  $L_z = 200$  km,  $V_n = 10^3$  m/sec,  $6.7 \times 10^2$  m/sec,  $3.3 \times 10^2$  m/sec, and  $10^2$  m/sec. We note that  $r_{cr}$  decreases substantially as  $V_n$  decreases from

$10^3$  m/sec to a nominal ionospheric value of  $10^2$  m/sec. For conductivity ratios  $\sigma_{||}/\sigma_{\perp} \gtrsim 10^5$  we find that  $r_{cr} \lesssim 300$  m when  $V_n = 10^2$  m/sec; this value of  $r_{cr}$  is similar to the barium cloud results.

#### IV. DISCUSSION

We have developed a relatively simple procedure to determine the critical transverse scale size of an ionospheric plasma cloud or striation based upon the 3D model of Drake et al. (1988). The critical radius is given by (9) where  $z_{cr}$  is determined from (8), i.e.,  $\Gamma_0 = \Gamma_{c0}$ . We find the somewhat surprising result that 'thin' clouds are more unstable than 'fat' clouds (all other parameters being equal). That is, clouds are unstable for  $r_c < r_{cr}$ , while they are stable for  $r_c > r_{cr}$ . Applying this model to barium clouds released at  $\sim 180$  km we find that  $r_{cr} \lesssim 100$  m; this result is consistent with observational evidence of frozen clouds (or fingers) for  $r_c \sim 100$ 's m [Linson, 1972]. Applying this model to nuclear striations leads to a broad range of  $r_{cr}$  because of the variability of the physical parameters of the system. We find that for weakly collisional plumes (i.e.,  $\sigma_{||}/\sigma_{\perp} \gtrsim 10^6$ ) that  $r_{cr} \lesssim$  few kms, while for strongly collisional plumes (i.e.,  $\sigma_{||}/\sigma_{\perp} \lesssim 10^5$ ) that  $r_{cr} > 10$  km.

Although these results are interesting, there are two problems which need to be addressed regarding the development of a freezing scale model based on 3D dynamics. The first problem involves the observed size of frozen barium cloud striations ( $r_c \sim 100$ 's m). This scale size is not described by our 3D model. An explanation for this is the following. During the early stages of barium cloud evolution, the cloud is relatively diffuse and is not well-described by the 3D waterbag model assumed in Drake et al. (1988). The cloud is not in equilibrium and evolves dynamically with its 'backside' developing a steep gradient. The 'backside' eventually becomes unstable and the cloud 'breaks-up' into smaller clouds (or

fingers). We speculate that the observed freezing scale size is determined during the initial structuring of the cloud. The newly formed smaller clouds may have a density profile similar to the waterbag equilibrium discussed in Drake et al. (1988) (or may evolve into such a profile), and thus, would be stable to further structuring because of 3D effects.

Applying this reasoning to nuclear striations suggests that it is crucial to understand and model the initial onset of structure in the nuclear environment in order to determine the physical scale sizes of striations. However, unlike the barium cloud case, it is not clear that the initial set of scale sizes will be stable to further structuring because of 3D effects. This is because the broad range of physical parameters (e.g.,  $\sigma_{||}/\sigma_{\perp}$ ,  $L_z$ ,  $V_n$ , etc.) in a nuclear environment leads to a broad range of critical scale sizes  $r_{cr}$ ; as shown in Section III,  $r_{cr} \approx 10's \text{ m} - 100's \text{ km}$ . It is likely that there will be striations formed with  $r_c < r_{cr}$  so that further structuring can occur. Nevertheless, early time structuring ( $t \sim \text{few min}$ ) will probably play an important role in setting up a distribution of striation scale sizes which may persist into late time, and hence should be more thoroughly investigated.

For example, the field-aligned striations which formed during the Checkmate event had transverse scale sizes in the range 300 - 1800 m, most of them were in the range 500 - 700 m (Chesnut, private communication). These striations were produced within a few minutes after the burst. To estimate  $r_{cr}$  for Checkmate, we consider an aluminium plasma with  $n \approx 10^8 \text{ cm}^{-3}$ ,  $T_e = T_i \approx .3 \text{ eV}$ ,  $B = 0.3 \text{ G}$ , and  $v_{in} \approx 1 \text{ sec}^{-1}$ . For these parameters we find that  $\sigma_{||}/\sigma_{\perp} \approx 2 \times 10^4$ . From Fig. 3 we note that  $r_{cr} \approx 2 \text{ km}$  (for  $M = 100$ ,  $V_n = 10^3 \text{ m/sec}$ , and  $L_z = 200 \text{ km}$ ) which is larger than the observed striation radii. However, if we were to take  $M$  somewhat larger and  $V_n$

somewhat smaller (e.g.,  $M = 200$  and  $V_n = 400$  m/sec) we find that  $r_{cr} = 300$  m. For these parameters, the Checkmate striations would be stable to further structuring by the  $\underline{E} \times \underline{B}$  instability; the important scale sizes and relevant power spectra would then be determined at early time.

Up to this point, the discussion has focussed on the transverse scale size of frozen barium or nuclear clouds. Here, frozen refers to the property that the plasma cloud is stable to further large-scale structuring by the gradient drift instability. This leads to the second problem: what is the relationship between the frozen transverse scale size and the freezing scale length? The freezing scale length is defined as the scale size at which there is a transition in the power law of the power spectral density (for example, from  $\sim k^{-1.5}$  to  $\sim k^{-2.5}$ ). The details of the power spectral density depend not only upon the transverse scale of the cloud or striation, but upon the distribution of transverse scale sizes of striations, as well as the density profiles themselves (i.e., edge effects) (Zabusky et al., 1986; Prettie, 1988). Calculating these quantities is not within the scope of the present 3D model; 3D numerical simulations will be required to better understand many of these issues.

In conclusion, we have presented quantitative estimates of the critical scale size ( $r_{cr}$ ) of ionospheric plasma striations based on the 3D model developed at NRL (Drake et al., 1988). We have considered parameters typical of both barium clouds and nuclear striations. The relevance of these results to the 'freezing' problem is described as follows. If the initial set of striations has scale sizes such that  $r_c > r_{cr}$  then they will be stable to further large-scale structuring because of 3D effects, i.e., they will be 'frozen'. This hypothesis is consistent with barium cloud observations. This leads to the important conclusion that the late time

characteristics of striations (e.g., scale sizes, power spectra, etc.) are determined at early time. Thus, a thorough investigation of early time structuring processes is needed. Applying this idea to the nuclear environment suggests that the structuring of the debris-air shell (being studied experimentally by the NRL laser group), as well as the possible structuring of the deposition region, should be vigorously pursued. Finally, we add that our results are preliminary in the sense that they are based upon an idealized cloud model. To better understand and quantify the nature of 3D effects for realistic clouds requires 3D simulation studies; such studies are currently being conducted at NRL.

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# APPENDIX

We present an explicit expression for  $r_{cr}$  as a function of the parameters (e.g.,  $M$ ,  $V_n$ ,  $T_e$ ,  $T_i$ ,  $\sigma_{||}/\sigma_{\perp}$ ,  $L_z$ , etc.). Based upon the definition  $z_c = (L_z/r_c)(\sigma_{\perp}/\sigma_{||})^{1/2}$ , we rewrite  $\Gamma_{c0}$  (Eq. (9)) as follows

$$\begin{aligned} \sqrt{2} \frac{L_z}{r_c} \left( \frac{\sigma_{\perp}}{\sigma_{||}} \right)^{1/2} (M+2)^{-1} & \quad r_c \ll L_z \left( \sigma_{\perp}/\sigma_{||} \right)^{1/2} \\ \Gamma_{c0} = \frac{3\sqrt{2}}{2} \frac{L_z}{r_c} \left( \frac{\sigma_{\perp}}{\sigma_{||}} \right)^{1/2} (M+3)^{-1} & \quad r_c = L_z \left( \sigma_{\perp}/\sigma_{||} \right)^{1/2} \quad (A1) \\ \frac{ML_z \left( \sigma_{\perp}/\sigma_{||} \right)^{1/2}}{2r_c/\pi + ML_z \left( \sigma_{\perp}/\sigma_{||} \right)^{1/2}} & \quad r_c \gg L_z \left( \sigma_{\perp}/\sigma_{||} \right)^{1/2} \end{aligned}$$

Noting that the critical radius is determined by  $\Gamma_0 = \Gamma_{c0}$  we find that  $r_{cr}$  is given by

$$\begin{aligned} \sqrt{2} \frac{V_n}{v_i} \frac{L_z^2}{\rho_i} \frac{\sigma_{\perp}}{\sigma_{||}} (M+2)^{-1} & \quad r_{cr} \ll L_z \left( \sigma_{\perp}/\sigma_{||} \right)^{1/2} \\ r_{cr} = \frac{3\sqrt{2}}{2} \frac{V_n}{v_i} \frac{L_z^2}{\rho_i} \frac{\sigma_{\perp}}{\sigma_{||}} (M+3)^{-1} & \quad r_{cr} = L_z \left( \sigma_{\perp}/\sigma_{||} \right)^{1/2} \quad (A2) \\ \frac{\pi}{2} \left( \frac{V_n}{v_i} \frac{L_z^2}{\rho_i} \frac{\sigma_{\perp}}{\sigma_{||}} - ML_z \left( \frac{\sigma_{\perp}}{\sigma_{||}} \right)^{1/2} \right) & \quad r_{cr} \gg L_z \left( \sigma_{\perp}/\sigma_{||} \right)^{1/2} \end{aligned}$$

where  $v_i^2 = (T_e + T_i)/m_i$  and  $\rho_i = v_i/\Omega_i$ .

It is clear from (A2) that  $r_{cr}$  is directly proportional to  $L_z$  and  $V_n$ , and inversely proportional to  $T_e$ ,  $T_i$ , and  $\sigma_{||}/\sigma_{\perp}$ . The dependence of  $r_{cr}$  on  $M$  depends upon the value of  $r_{cr}$  relative to  $L_z(\sigma_{\perp}/\sigma_{||})^{1/2}$ . Interestingly, we find that clouds are always stable when  $r_c \gg L_z(\sigma_{\perp}/\sigma_{||})^{1/2}$  and

$$M > \frac{V_n}{v_i} \frac{L_z}{\rho_i} \left( \frac{\sigma_{\perp}}{\sigma_{||}} \right)^{1/2}. \quad (A3)$$

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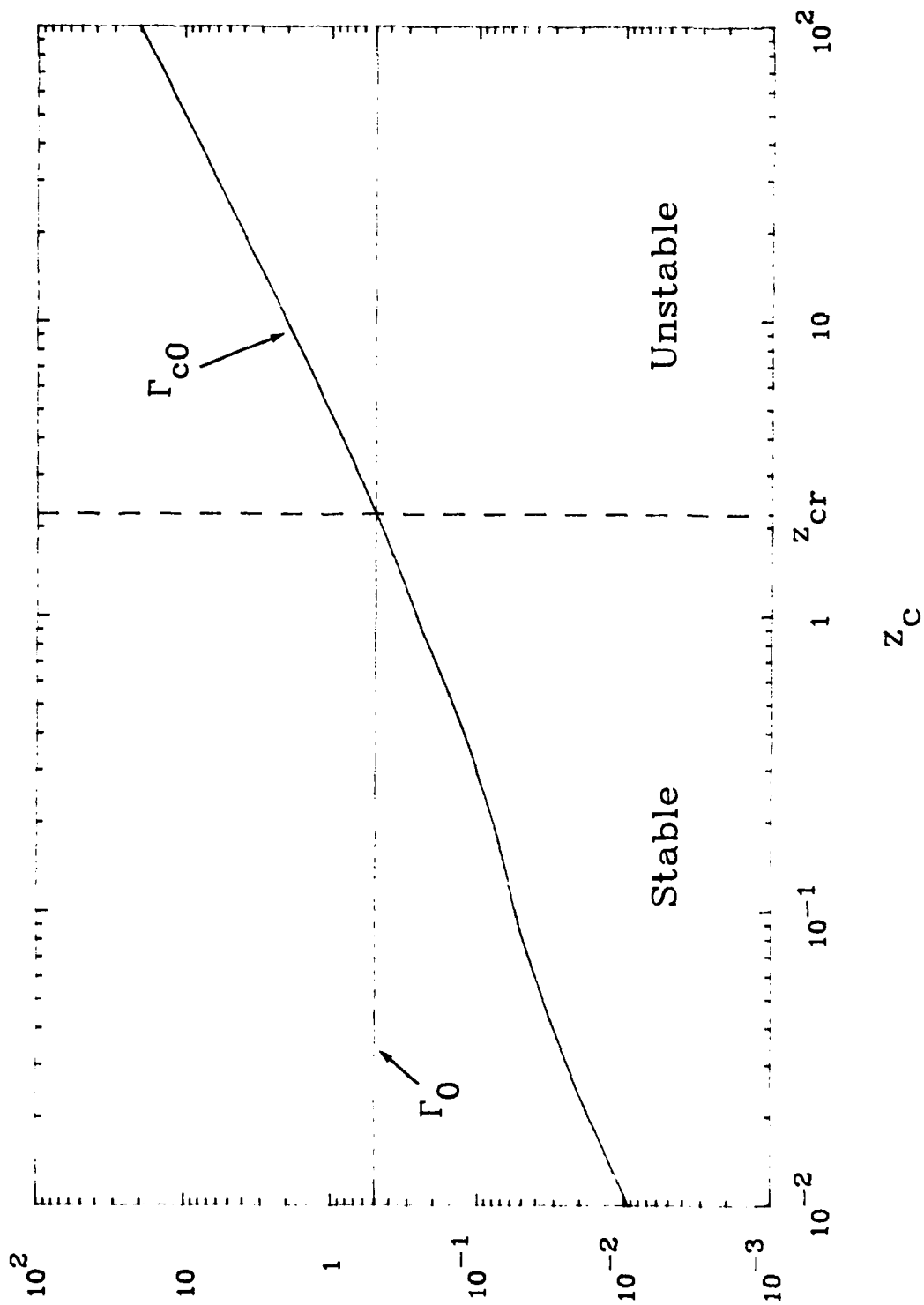


Fig. 1) Plot of  $\Gamma_0$  and  $\Gamma_{c0}$  vs.  $z_c$  for  $M = 5.0$ .  $z_{cr}$  is determined by the value of  $z_c$  for which  $\Gamma_0 = \Gamma_{c0}$ . Clouds are stable for  $\Gamma_0 > \Gamma_{c0}$  (or  $z_c < z_{cr}$ ), and are unstable for  $\Gamma_0 < \Gamma_{c0}$  (or  $z_c > z_{cr}$ ) as indicated in the figure.

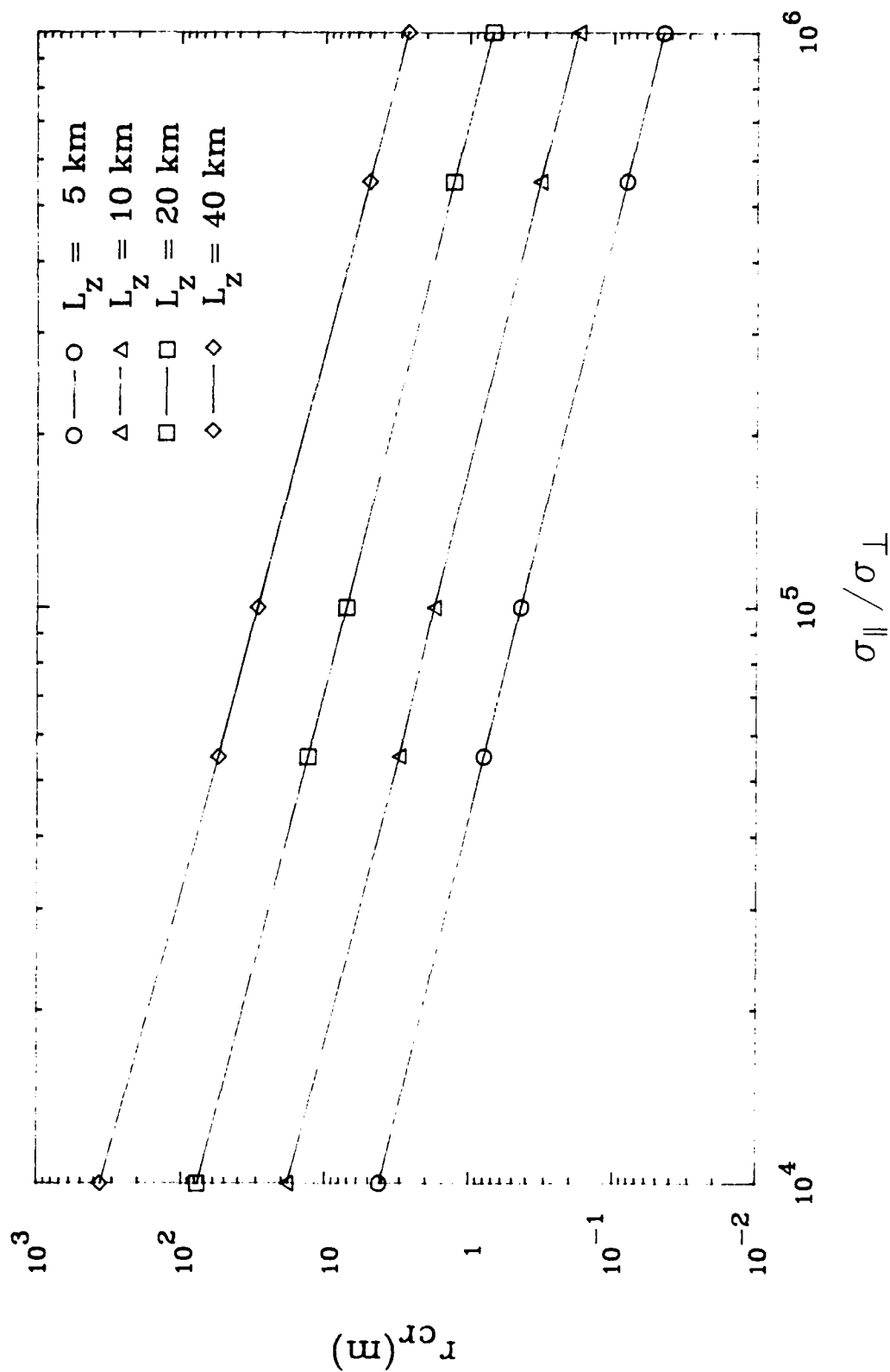


Fig. 2) Plot of  $r_{cr}(m)$  vs.  $\sigma_{\parallel}/\sigma_{\perp}$  for  $M = 10$ ,  $T_e = T_i = 0.1 \text{ eV}$ ,  $B = 0.3 \text{ G}$ ,  $V_n = 100 \text{ m/sec}$ , and  $L_z = 5 \text{ km}$ ,  $10 \text{ km}$ ,  $20 \text{ km}$ , and  $40 \text{ km}$ . These values are typical of barium clouds released at  $\sim 180 \text{ km}$ .

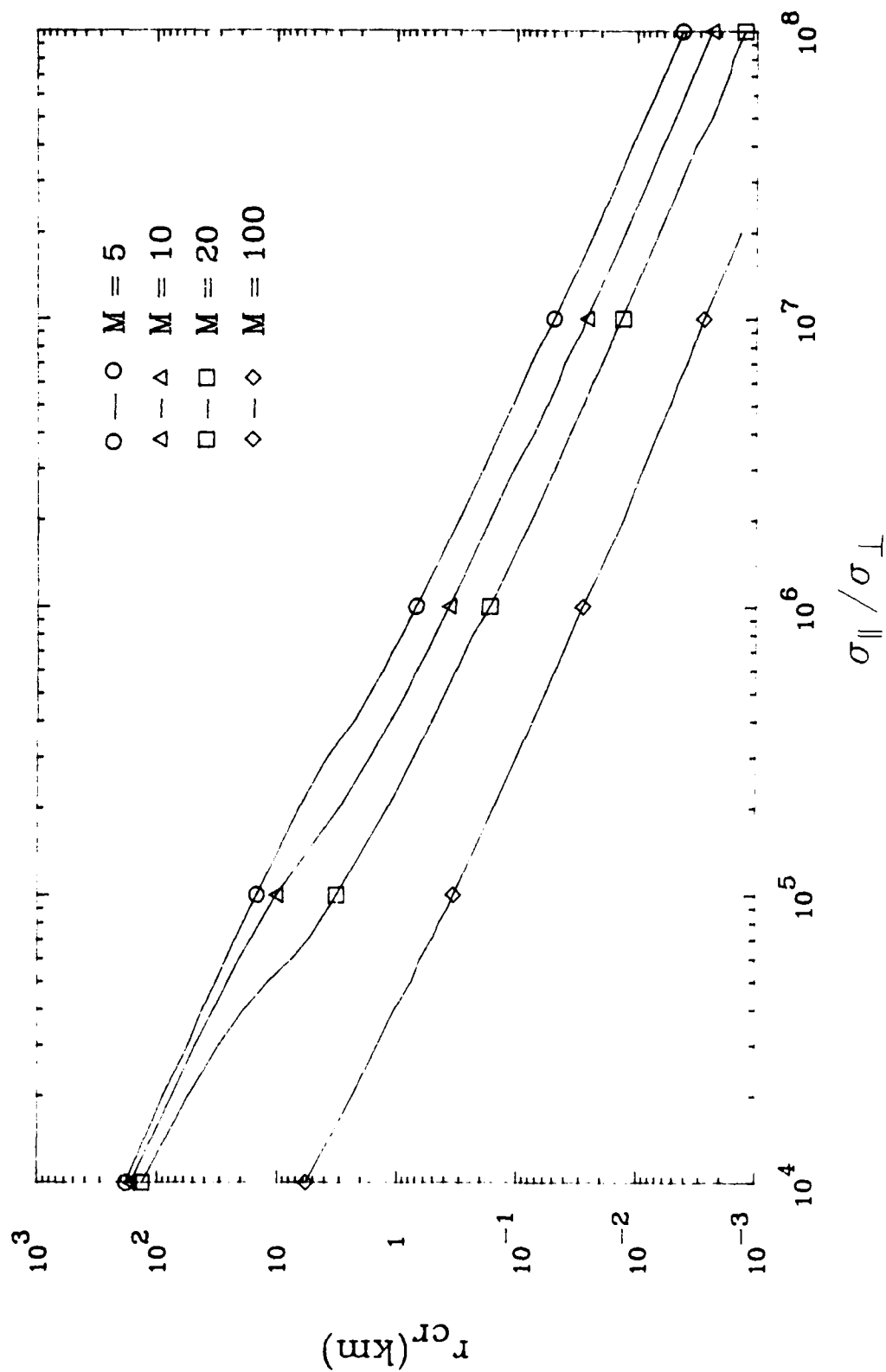


Fig. 3) Plot of  $r_{cr}$  (km) vs.  $\sigma_{\parallel}/\sigma_{\perp}$  for  $L_z = 200$  km,  $V_n = 1$  km/sec,  $T_e = T_i = 0.3$  eV, and  $M = 5.0, 10.0, 20.0$ , and  $100.0$ . These values are representative of a nuclear environment.

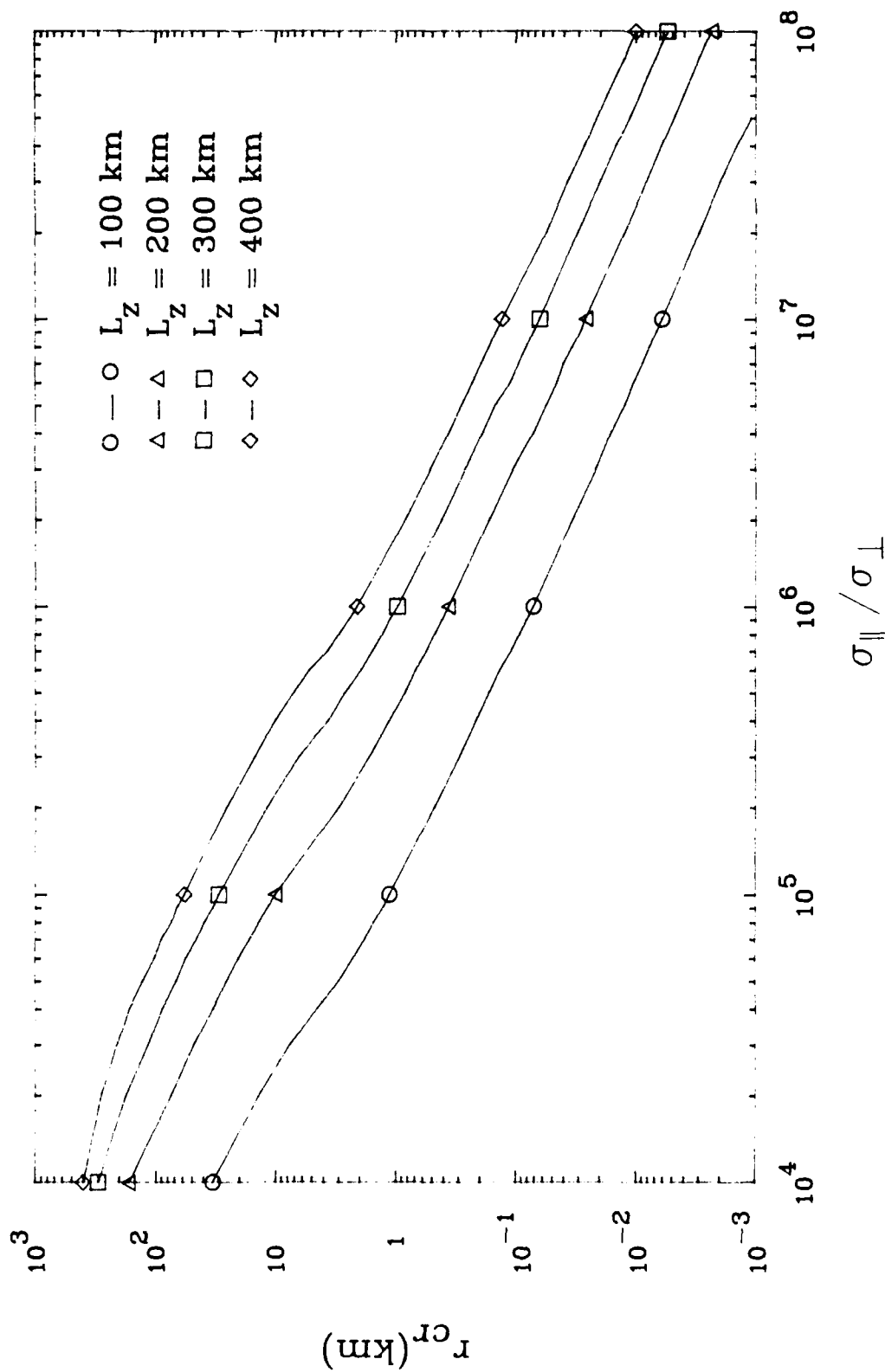


Fig. 4) Plot of  $r_{cr}$  (km) vs.  $\sigma_{||}/\sigma_{\perp}$  for  $M = 10$ ,  $V_n = 1$  km/sec,  $T_e = T_i = 0.3$  eV,  $B = 0.3$  G and  $L_z = 100$  km, 200 km, 300 km, and 400 km.

These values are representative of a nuclear environment.

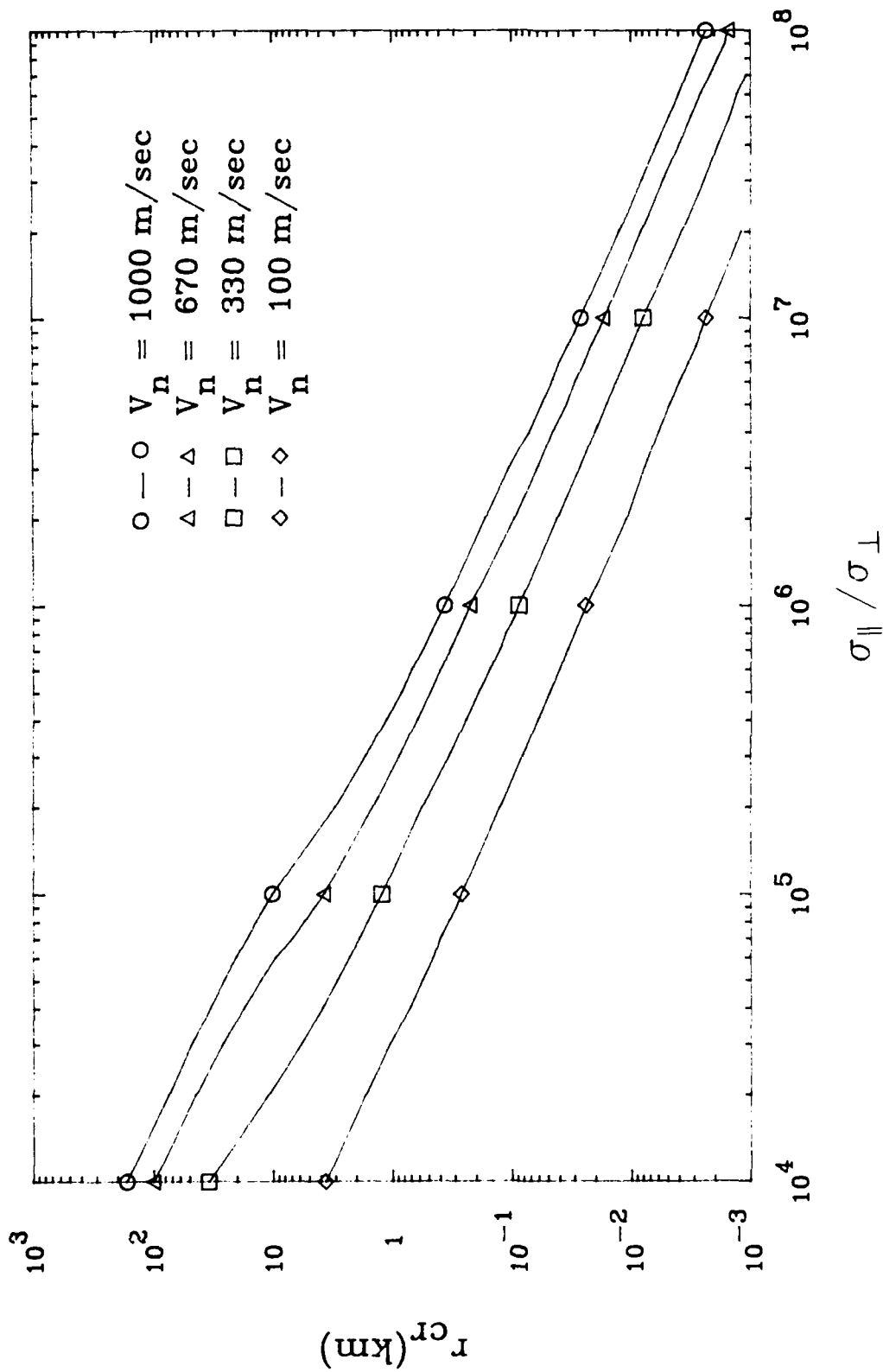


Fig. 5) Plot of  $r_{cr}$  (km) vs.  $\sigma_{\parallel}/\sigma_{\perp}$  for  $M = 10$ ,  $L_z = 200 \text{ km}$ ,  $T_e = T_i \approx 0.3 \text{ eV}$ ,  $B = 0.3 \text{ G}$ , and  $V_n = 1000 \text{ m/sec}$ ,  $670 \text{ m/sec}$ ,  $330 \text{ m/sec}$ , and  $100 \text{ m/sec}$ . These values are representative of a nuclear environment.



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